Three-Dimensional Neutronics Analysis for ITER Divertor Cassette Design Options

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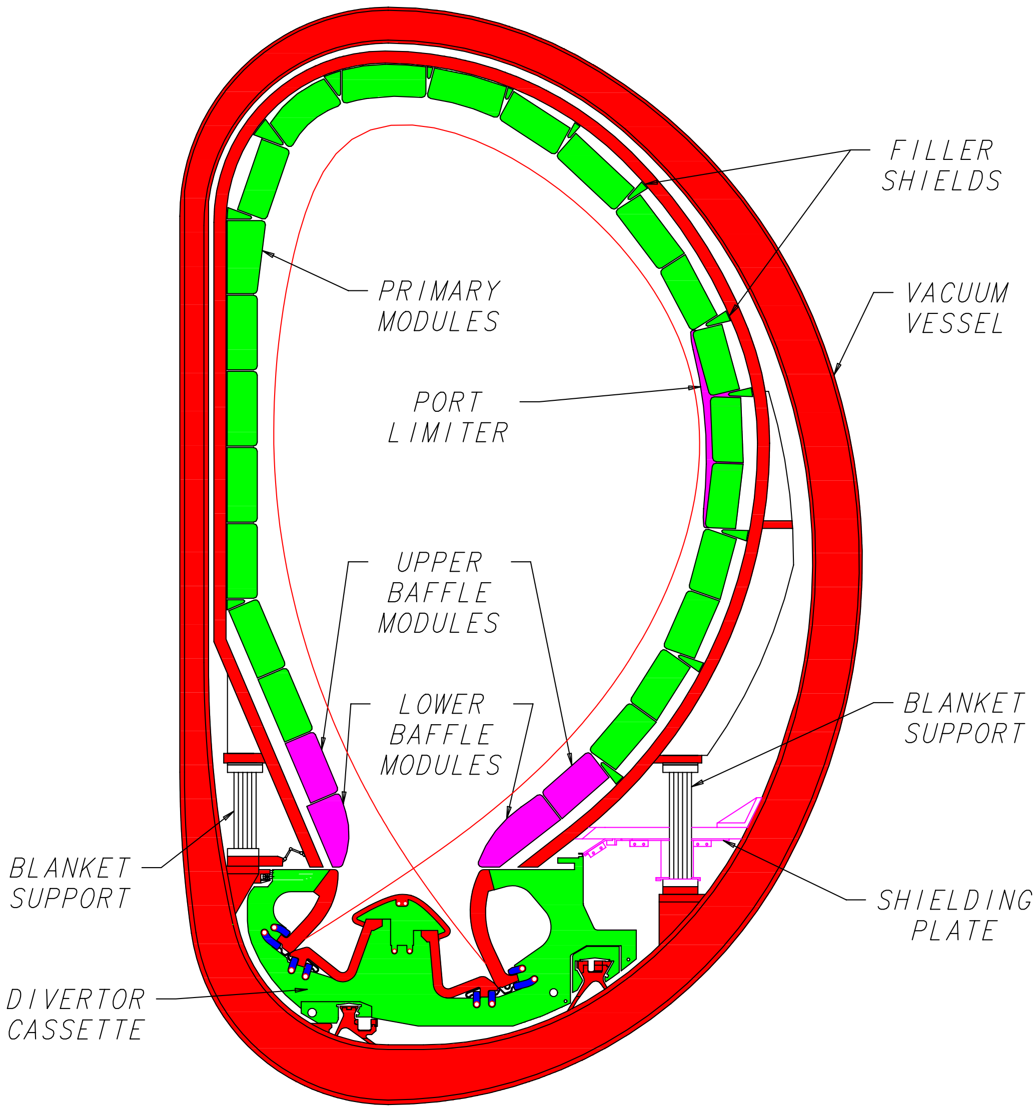
ITER Final Design



Divertor Design Features

- ITER employs modular single null divertor
- 60 cassettes mounted on toroidal rails
- Each cassette is 5 m long, 2 m high and 0.5 - 1.0 m wide, and weighs 25 tones
- A dome is positioned immediately below X-point
- Accommodates divertor channels for inner and outer legs of separatrix
- Both channels pumped through pumping ducts in cassette body
- PFC attached to dome and surfaces surrounding divertor channels

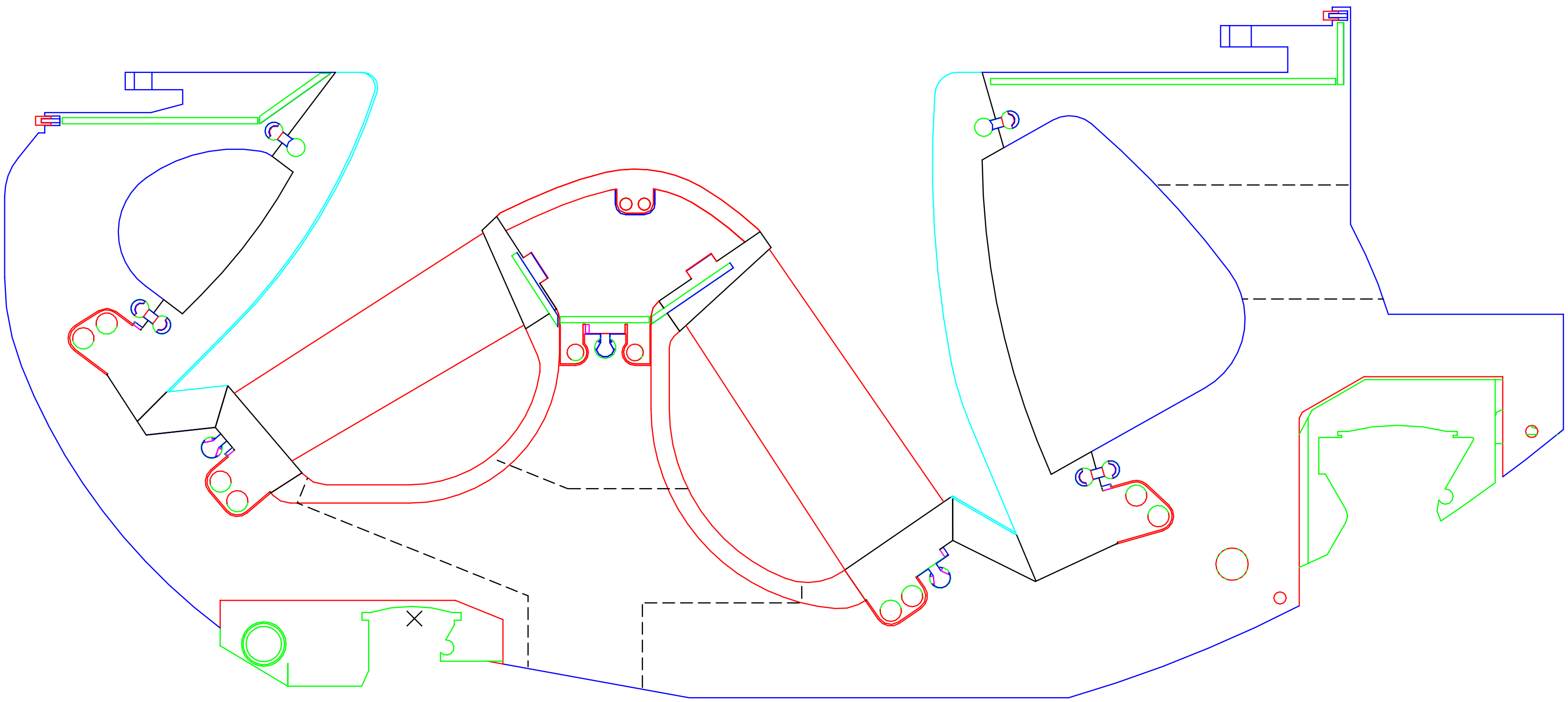
Divertor Cassette Design Options

Divertor cassette design has undergone several changes to improve its performance

Two design options considered:

- Design option with wings and gas boxes under dome
- The reference design including extended dome, elimination of wings, and using a thick liner in front of pumping duct

Divertor Cassette Design Option with Wings



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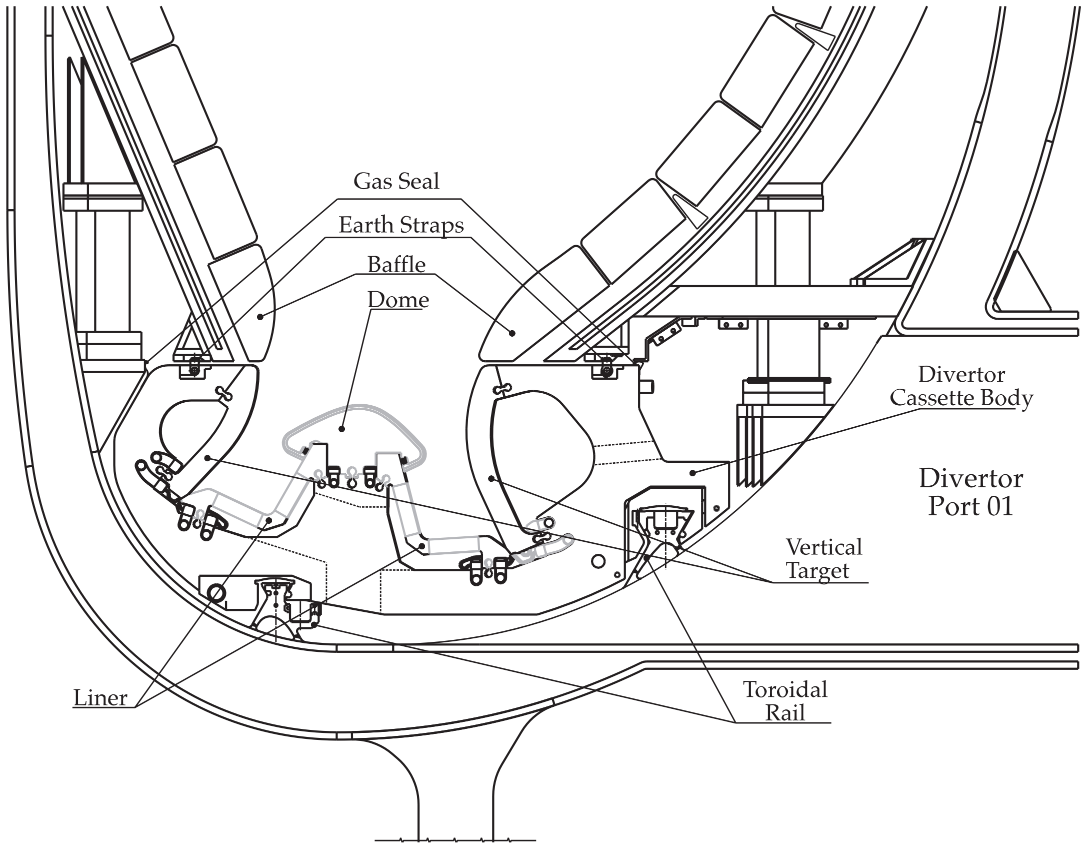
Reference Divertor Cassette Design



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Objectives

- Determine neutron wall loading distribution
- Calculate nuclear parameters in the divertor cassette options
- Assess feasibility of vacuum vessel rewelding in the divertor region
- Evaluate damage and heating in the TF coils due to streaming in divertor ports
- Results presented for the cassette design option with gas boxes and wings and for the current reference design taking into account changes in geometry and material composition

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Calculation Procedure

- Detailed 3-D geometrical configuration of ITER divertor cassette modeled
- Continuous energy Monte Carlo code MCNP-4A
- Cross section data based on FENDL-1
- Source sampled from pointwise source distribution in ITER plasma
- Used 50,000 source particles yielding statistical uncertainties less than 5%
- Results normalized to nominal fusion power of 1500 MW
- End of life parameters normalized to fluence of 1 MW.a/m^2

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3-D Divertor Cassette Model

- Geometrical complexity mandates 3-D modeling
- Model represents a nine degree toroidal sector (1/40) of ITER
- It includes one and half cassettes with associated 1 cm gaps
- Each cassette divided into 103 regions to provide detailed spatial distribution of nuclear heating and radiation damage
- Layered configurations of dome PFC and vertical targets modeled accurately
- Separate regions included to represent mechanical attachments and coolant pipe connections

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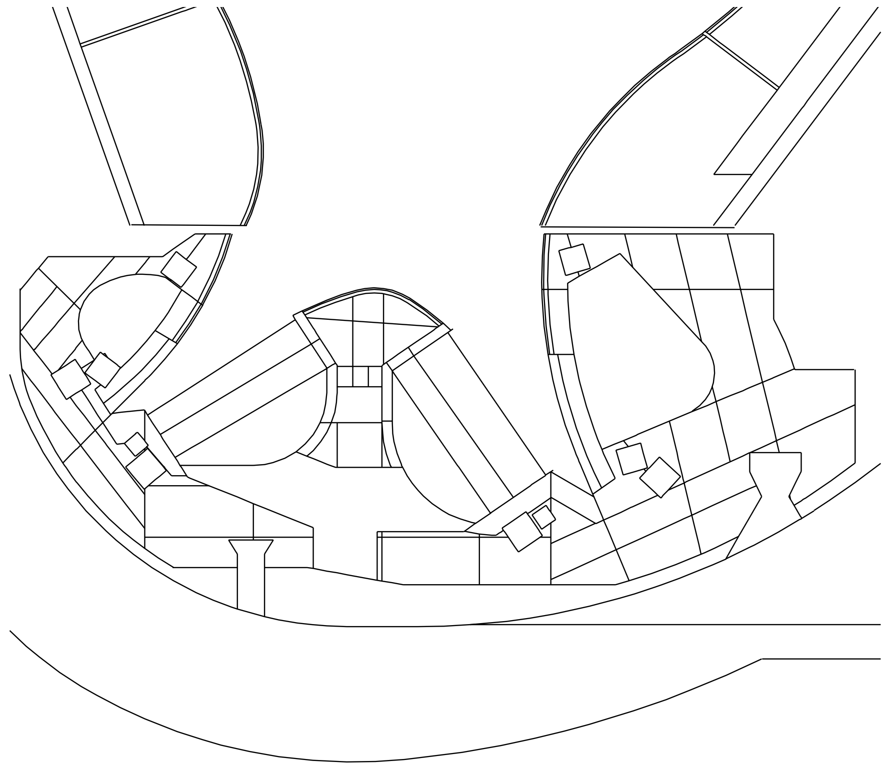
Vertical cross section of ITER cassette model



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Integrated 3-D Model

- Integrated model includes FW, blanket with coolant manifolds and back plates, VV, TF coils, central solenoid, and PF coils
- While Be is used as PFC at FW, tungsten is used for baffle modules above the divertor cassette
- All toroidal and poloidal gaps included
- Major VV penetrations included
- Model includes half a TF coil and half a divertor port
- Divertor port wall is 20 cm thick and consist of 80% 316SS and 20% water. No additional shielding is included

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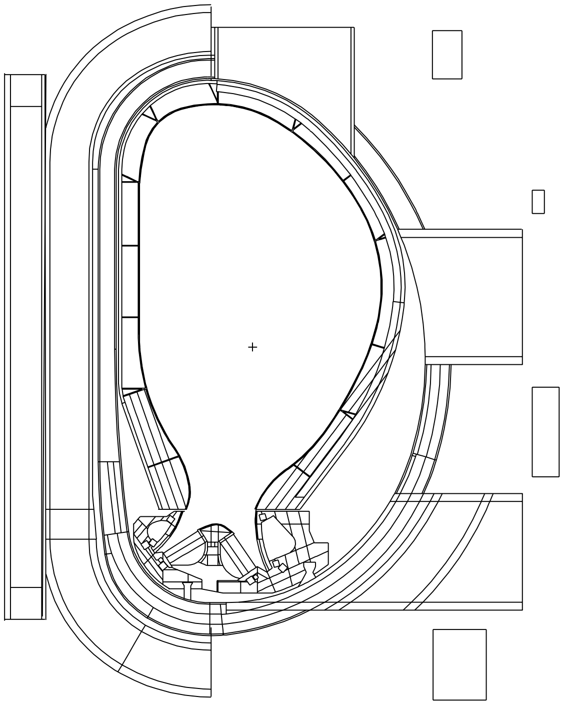
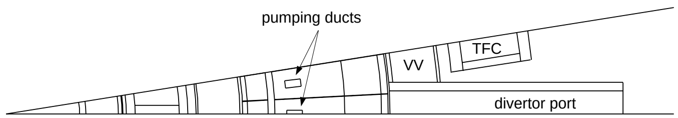
Integrated ITER model



Vertical Cross Section



Horizontal Cross Section at Z= -6 m

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Divertor Cassette Material Composition

	Design with Wings	Reference Design
Dome PFC	1 cm W 2 cm 75% Cu, 25% water Dome body 75% SS, 25% water	1 cm W 2.2 cm 83% Cu, 17% water Dome body 85% SS, 15% water
Wings	16% W, 79% Cu, 5% water packing fraction: 21% outer, 26% inner	NA
Gas Box Liner	8% W, 74% Cu, 18% water	9% W, 8% Cu, 28% SS, 6% water 18% W, 18% Cu, 56% SS, 8% water
Vertical Targets	top section: 1 cm W 2.5 cm 82% Cu, 18% water back region 97% SS, 3% water lower section: 5.5 cm 89% C, 4% Cu, 7% water back region 97% SS, 3% water	top section: 1 cm W 2.5 cm 82% Cu, 18% water back region 97% SS, 3% water lower section: 5.5 cm 89% C, 4% Cu, 7% water back region 97% SS, 3% water
Cassette Body	80% SS, 20% water	80% SS, 20% water

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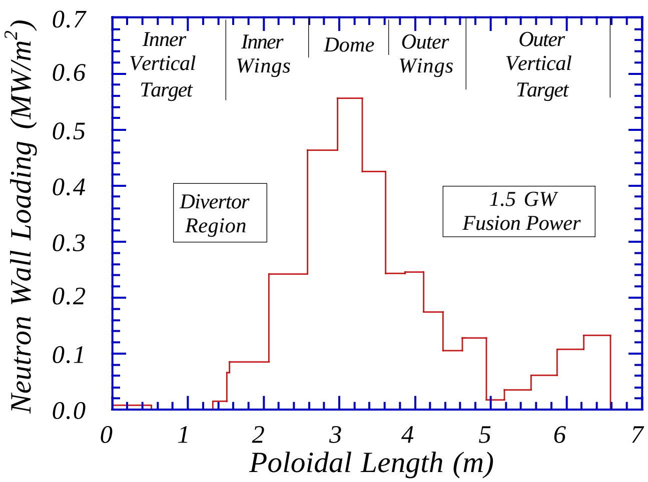
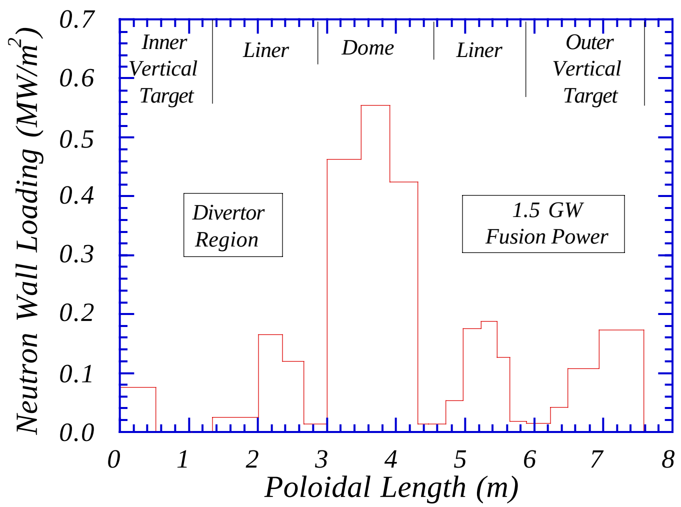
Neutron Wall Loading Distribution



Design with Wings

0.16 MW/m^2 average wall loading



Reference Design

0.14 MW/m^2 average wall loading

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Peak Nuclear Parameters in Cassette

Zone	Power Density (W/cm^3)		dpa in Structure (dpa/FPY)		He Production in Structure (appm/FPY)	
	Reference Design	Previous Design	Reference Design	Previous Design	Reference Design	Previous Design
Dome PFC	16.4	16.4	3.5 Cu	3.5 Cu	31 Cu	31 Cu
Dome Body	3.8	3.9	1.9 Cu	2.1 Cu	16 Cu	17 Cu
Central Body	0.5	0.4	0.1 SS	0.1 SS	2.9 SS	2.5 SS
Outer Leg	0.6	0.5	0.12 SS	0.1 SS	3.9 SS	3.7 SS
Inner Leg	0.5	0.3	0.06 SS	0.04 SS	2.5 SS	2 SS
Outer Vertical Target	15	12	1.1 SS	0.8 SS	12 SS	9 SS
Inner Vertical Target	11	8.4	0.5 SS	0.3 SS	4.9 SS	3.1 SS
Outer Dump Target	1.3	1.5	0.5 Cu	0.64 Cu	4 Cu	5.1 Cu
Inner Dump Target	1	0.9	0.3 Cu	0.24 Cu	2 Cu	1.1 Cu
Outer Liner	2.1	0.8	0.9 Cu	0.3 Cu	9.6 Cu	1.6 Cu
Inner Liner	1.9	0.7	0.8 Cu	0.3 Cu	9.3 Cu	1.5 Cu

Nuclear Parameters in Divertor Cassette

- Largest heating and damage occurs in the dome PFC with full view of the plasma. Power density in the W PFC at the dome is 16.4 W/cm^3
- W PFC at top of vertical targets experience relatively high levels of heating and damage
- Heating and damage values drop rapidly as one moves deeper in cassette body
- Nuclear parameters in inboard side of cassette are lower than in outboard side

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Impact of Changes in Reference Design

- Nuclear heating and damage in dome PFC of reference design are similar to those in design option with wings
- Coolant connections and mechanical attachments at bottom of dome experience a factor of 20 lower heating and damage
- Configuration of outer vertical target results in upper part having full view of plasma and higher nuclear parameters
- Nuclear parameters in dump targets slightly different due to different configurations of vertical targets and dump targets
- Liners exposed to direct source neutrons except for top regions shielded by extended dome

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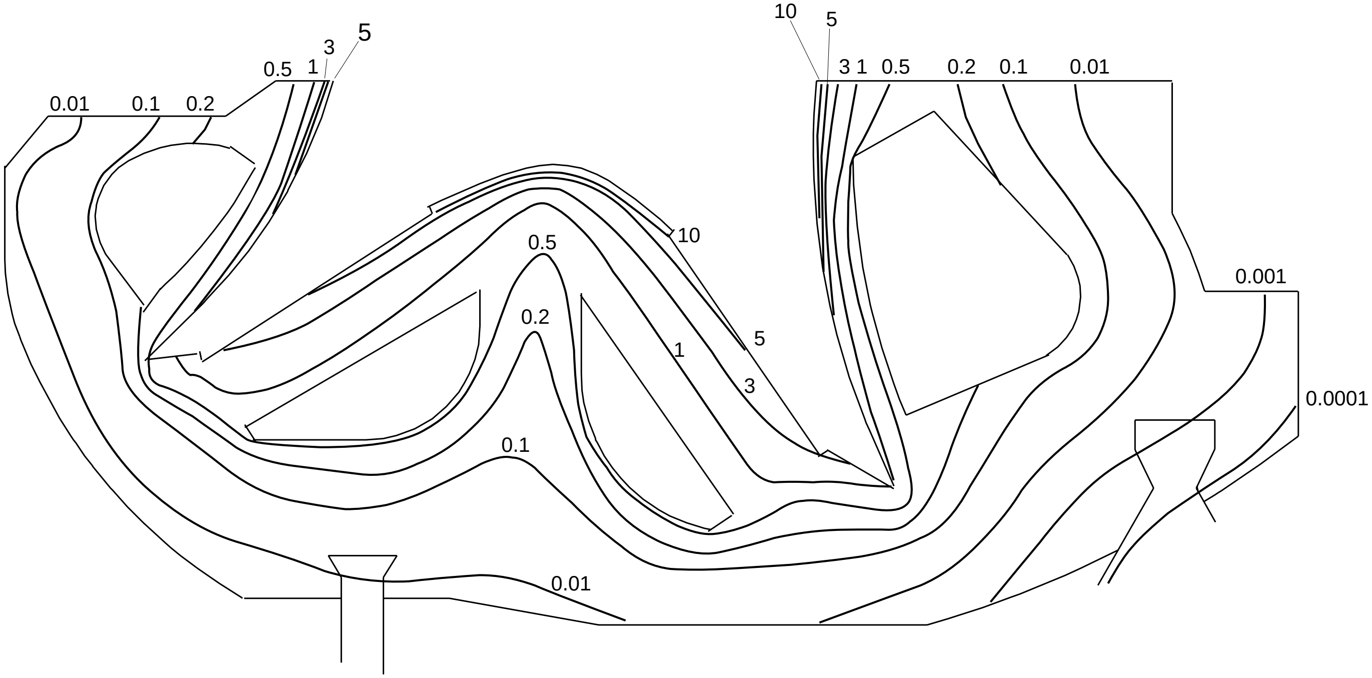
Nuclear Heating (W/cm^3) Map in Divertor Cassette Design Option with Wings



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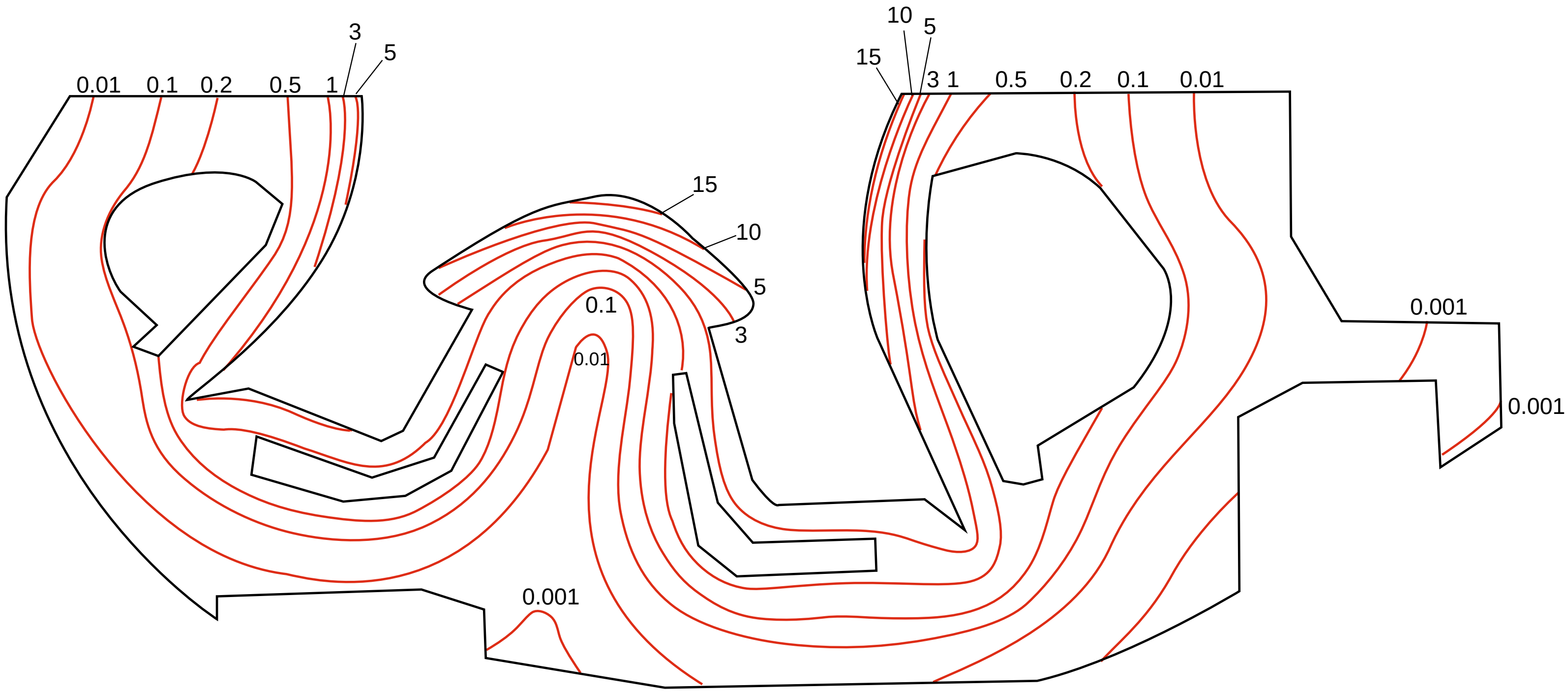
Nuclear Heating (W/cm^3) Map in Reference Divertor Cassette Design



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Total nuclear heating (MW) in 60 divertor cassettes

Zone	Reference Design	Design with Wings
Dome	40	31
Vertical Targets	23	24
Wings	0	29
Liner/Dump Target	25	4
Central Cassette Body	5	5
Outer Cassette Body	7	7
Inner Cassette Body	2	2
Total	102	102

Streaming and Impact on Vacuum Vessel

- Pumping duct at bottom of cassette has 17.5 cm toroidal width
- Poloidal width of duct outlet is 45 cm in reference design compared to 37.5 cm in design option with wings
- Effective shielding provided by liner in reference design similar to that provided by wings in front of duct in previous design option
- Peak He production values in VV behind duct are 0.22 appm/FPY in reference design and 0.18 appm/FPY in previous design
- Another area of concern is along the divertor port. Peak He production is 0.036 appm/FPY at location where port wall joins with front VV wall
- Rewelding divertor port and parts of VV behind pumping ducts is feasible

Magnet Radiation Effects in Divertor Region

- No credit taken for attenuation in coolant pipes, cryopumps, components in port

	Front surface	Side surface	Design limit
Coil case power density (kW/m^3)	0.080	0.126	2
Winding pack power density (kW/m^3)	5.12×10^{-3}	6.38×10^{-3}	1
Insulator dose (Rad/FPY)	4.46×10^{6}	6.78×10^{6}	10^{9}
Fast neutron fluence (n/cm^2 per FPY)	6.27×10^{15}	1.10×10^{16}	10^{19}
Copper dpa (dpa/FPY)	2.38×10^{-6}	4.46×10^{-6}	6×10^{-3}

- Radiation effects higher at side surface due to effect of streaming through port
- Radiation effects much lower than radiation limits and TF coils are well protected from streaming into divertor ports

Total Nuclear Heating in TF Coils

- Total nuclear heating in parts of 20 TF coils in divertor region is 2.1 kW with 1.6 kW contributed by parts adjacent to divertor port
- Calculations that included inter-coil structures and midplane port streaming gave total heating of 7.6 kW in TF coils and inter-coil structure in divertor region
- A 23 cm thick plate (75% SS and 25% water) is needed between VV and blanket to allow personnel access two weeks after shutdown in area around divertor port
- This shield reduces nuclear heating in divertor region to 0.5 kW
- Total nuclear heating in TF coils should not exceed 17 kW
- Adding calculated nuclear heating for different regions of the TF coils including streaming through all VV ports yields total nuclear heating of about 7 kW

Conclusions

- Peak neutron wall loading is 0.56 MW/m^2 at dome
- Largest heating and damage is in dome PFC with power density of 16.4 W/cm^3
- Nuclear parameters in inboard side of cassette lower than in outboard side
- Local nuclear parameters in components of reference cassette design are similar or lower than in cassette design option with wings
- Total nuclear heating in the 60 divertor cassettes is 102 MW for both designs
- Peak helium production in VV and divertor port implies that rewelding is feasible
- TF coils are well protected from radiation streaming into divertor ports
- Total heating in TF coils and inter-coil structure in divertor region is only 0.5 kW when a 23 cm plate shield used between the VV and blanket above divertor port

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